PREFACE

GASEOUS CORE REACTORS

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Received January 17, 1985
Accepted for Publication January 17, 1985

INTRODUCTION

Gaseous core reactors use a gaseous fissile material as fuel for power generation. The fissioning gas "drives" the reactor core; a wide variety of physical arrangements using external or internal moderation of neutrons and methods of containing the gas and extracting the energy have been suggested. Scientific research has been conducted on candidate concepts for the past 30 years, but no engineering feasibility study has been completed or reported in the open literature. Most of the research has been limited to conceptual phase studies, with a few experimental programs conducted to determine basic neutronics and fluid characteristics and the associated materials and materials interaction studies.

The promise of significant enhancement in key aspects of nuclear power generation—including improved fuel utilization, safety, plant efficiency, special high-performance features, lead-following capabilities and power conversion optimization, and its unique potential for space power applications—has kept the gaseous core area *alive* throughout these decades of erratic directions in the development of nuclear power. Periods of significant research activity have been followed by periods of very reduced efforts as funding cuts were effected.

The major research efforts in the United States were coupled to the nuclear space power program; these were essentially halted in 1973 when the program was canceled. Only two research programs on gaseous reactors continued during the 1970s: the mixed-flow gaseous reactor studies of Los Alamos National Laboratory (LANL) and United Technology Research Center (UTRC) *and* the cyclic gaseous core and heterogeneous gaseous reactor studies at the University of Florida. In addition, an effort to determine the potential and viability of gaseous core reactors for large commercial electric power generation was conducted under the Nonproliferation Alternative Systems Assessment Program (NASAP).

HISTORY

The first U.S. analytical studies of a gas core nuclear reactor were reported by Bell[1] of LANL in 1955. The reactors considered consisted of spherical cavities fueled with uranium hexafluoride (UF_6) gas and surrounded by heavy water (D_2O), beryllium, or graphite moderating reflectors. Other early analytical studies included those by Safonov[2] in 1958, Ragsdale and Hyland[3] in 1961, Hyland et al.[4] in 1963, and Herwig and Latham[5] in 1967. Since the critical particle densities of fissionable atoms in these systems correspond to molecular densities of gases at less than atmospheric pressure, the term "cavity reactor" was applied to these configurations. Configurations investigated included ^{233}U-, ^{235}U-, and ^{239}Pu-fueled systems; moderating-reflector materials considered included D_2O, beryllium, and graphite. The early studies were directed toward determining basic reactor physics parameters for these systems. Quantities calculated included critical masses, critical sizes, material reactivity worths, temperature reactivity coefficients, and potential breeding ratios. The results included evaluations of the relative effectiveness of the various fuels and moderating-reflector materials.

Analytical studies of gaseous core nuclear rocket engines were carried out by Plunkett[6] in 1967. Latham[7-9] and Latham et al.[10] conducted a series of extensive calculations (1966-1969) for a nuclear light-bulb (closed system) gaseous core reactor rocket engine. Coaxial flow (open system) gas core nuclear rocket engines were examined by Hyland[11] in 1971. The light-bulb and coaxial flow rocket engine systems are actually plasma core concepts, since the fissioning gases are assumed to be fully ionized. Parameters calculated again included critical masses, critical sizes, material worths, pressure, and temperature reactivity coefficients.

The first comparison of theoretical predictions with experimental data for a gaseous uranium core reactor was performed by Kikoin et al.[12] and reported in Moscow in 1959. Neutronic parameters and UF_6 behavior and conditioning with fluorinating agents were reported. The core had internal moderation (beryllium) and a graphite reflector. It went critical with 3340 g of uranium at 90% ^{235}U. The first such study in the United States was conducted by Mills[13] in 1962. In 1965, Jarvis and Beyers[14] of LANL made a comparison between theoretical predictions and experimental results for a D_2O reflected cavity reactor.

A series of critical experiments (1967-1969) was performed by Pincock et al.[15,16] and Kunze et al.[17] to test the ability of calculational procedures to evaluate criticality and other reactor parameters for a configuration closely resembling a coaxial flow system. A benchmark critical experiment, with spherical symmetry, on a gas core nuclear reactor concept was reported in 1972 by Kunze et al.[18] More recent experimental research programs on gas core reactors at LANL were reported in 1977 by Jarvis et al.[19]

Much of the early gas core reactor research was motivated by a desire by the U.S. National Aeronautics and Space Administration (NASA) to apply such systems for rocket propulsion in space. The original conceptual gaseous core nuclear rocket engines are specialized systems in which nuclear energy is generated and converted into thrust by the expulsion of heated gases in the plasma state. The application of gas core reactors to large central station electric power generation also had some early investigations. In 1969, Gritton and Pinkel[20] of the Rand Corporation reported one such study in which a 4000-MW(thermal) spherical gaseous core system with a 5-ft radius was analyzed at a pressure of 11 atm. The central cavity was surrounded by a moderating-reflector region and by banks of energy conversion devices; the core was in a plasma state.

A significant series of theoretical and experimental investigations on gaseous reactors was conducted by Williams and co-workers[21-28] at The Georgia Institute of Technology from 1968 through 1975. The concepts investigated centered on plasma cores, breeder reactor power plants, and advanced energy conversion systems, with extensive work on magnetohydrodynamic power systems.

A novel concept in gas core reactor design was introduced in 1974 by Diaz and Dugan[29,30] and Diaz et al.[31] The heterogeneous gas core reactor (HGCR) contains an array of moderator channels arranged in the gaseous core region. The HGCR thus has "internal" moderation and the core heterogeneity leads to significant thermal-hydraulic and energetic advantages along with improved technological feasibility with respect to other gas core reactor concepts. The HGCR was proposed for central station electric power generation and utilizes UF_6 gas at temperatures in the vicinity of 1000 K, in contrast to the plasma core concepts that were analyzed at significantly higher operating temperatures.

Other studies of gas core reactors applied to terrestrial power plants were reported by Rust and Clement[32] in 1976. They examined externally moderated UF_6 breeder reactor plants in which the blanket was molten salt; nonionized gases were used for the fuel.

A study by Lowry[33] in 1977 examined the mixed-flow gas core reactor (MFGCR) concept. The MFGCR employs a cluster of seven cavities externally moderated by beryllium and surrounded by a molten salt breeding blanket. The fuel gas mixture is passed through the core region by circulators to remove heat from the reactor and transport it to the intermediate heat exchangers. The multicavity concept provides better moderator distribution for the thermal reactor than a single reflected cavity and is necessary for the mixture temperature control required in the mixed flow concept. "Mixed flow" refers to gas mixing at the outlet of each cavity; a hot, slowly moving portion of the gas in the central part of the cavity (average exit temperatures of 1000 K) mixes with a cooler swirl flow of fuel gas that maintains contact with and cools the cavity wall to ~800 K. The vortex separation of the fuel gas into two streams in each cavity is accomplished by tangential injection slots in each cavity. The UF_6 fuel mixture enters a distribution manifold at the top of the reactor vessel, flows through the cavities, and is collected in a discharge manifold at the bottom of the vessel. The mixture leaves the vessel and flows through heat exchanger and a circulator. A second helium loop cools the moderator and blanket. An experimental program on the basic measurements of an MFGCR was used to prove predicted behavior of the concept.[34] The program, under NASA sponsorship, was conducted by LANL and UTRC at Los Alamos. Several critical configurations were successfully achieved and a nonfissioning simulation of vortex flow conditions was established; however, the program was prematurely aborted due to lack of continued financial support.

A significant departure from the above steady-state gas core systems is to be found in two pulsed gas core reactor concepts. The pulsed nuclear piston

(PNP) system, also known as the nuclear piston engine, was first studied by Kylstra et al.[35] Early studies were extended by Dugan[36] in 1976 and by Diaz et al.[37] in 1978. The PNP consists of a small pulsed gaseous core reactor enclosed by a moderating-reflector cylinder and piston assembly that operates on a thermodynamic cycle similar to the internal combustion engine. A sister concept is the pulsed gas generator (PGG) reactor proposed by Diaz et al.[38,39] in 1979. The gas generator is similar to the nuclear piston concept, except that it employs a core of fixed dimensions. The PGG concept has the advantage of mechanical simplicity, since it requires no moving piston; however, the PGG concept has a lower efficiency than the PNP system since it yields only thermal and no mechanical or shaft power. These pulsed systems have the advantage of attaining high peak values of variables, such as temperature and pressure, while maintaining relatively low cycle-averaged values. Power generation for these pulsed systems per chamber is of the order of a few megawatts for steady-state use and up to hundreds of megawatts for transient operation. Analytical studies on these pulsed cores were compared with experimental results obtained at the plasma core assembly at LANL (Ref. 39) and are reported in detail in the following three papers in this issue of *Nuclear Technology*.

The NASAP, started in 1977, included studies on a series of advanced but less developed reactor concepts with good potential for contributing to the goals of the U.S. nonproliferation and energy production program developed under President Carter's administration. As part of the NASAP evaluation, an integrated assessment of 11 advanced gaseous core nuclear power system concepts was performed. Five of the 11 well-documented concepts were judged as having the best potential for satisfying the objectives of the NASAP plan. The concepts selected on that basis for further evaluation were the mixed-flow reactor power plant, the closed cycle uranium plasma reactor', the UF_6 breeder reactor power plant, the heterogeneous gas core reactor, and the coaxial flow uranium plasma reactor (see Ref. 39).

A final report[40] entitled, "A Gaseous Core Reactor System Characterization for NASAP," reached additional basic conclusions obtained from the value engineering study of the reactor concepts, which we quote: "Group consensus indicated that either the Heterogeneous Gas Core Reactor concept or the Mixed-Flow concept could be used as a basis for the final plant design. Since inventories and resource utilization features of the Mixed-Flow reactor appeared more attractive, efforts (for the remainder of the contract) were concentrated on that concept," and

1. The UF_6-fueled reactors are the most attractive.
2. A carrier gas in addition to UF_6 is preferable for heat transport.
3. A low-enrichment cycle is most attractive for nonproliferation.
4. Increased inventory by the use of low-enriched UF_6 improves heat removal.
5. The sustainer/breeder cycle is most attractive for resource utilization.
6. Sustainer operation is feasible with a low-enrichment core.
7. Chemistry/materials and several other problems still require R&D.

It should be pointed out that the referenced NASAP report contains a very complete bibliography of the published literature for gaseous core reactor power systems.

CONCLUSIONS

Extensive analytical studies have been performed on many different gas core reactor concepts over the past 25 years. Neutronic experiments conducted during this period have been mostly restricted to verifying predictions for criticality and basic reactor physics parameters, such as reactivity coefficients and neutron lifetimes; space-, energy-, and time-dependent experiments[39] were recently completed at LANL. Basic materials, fluid flow, and heat transfer experiments have also been conducted for some of the gas core reactor concepts.

Several promising gas core reactor concepts exist for large central-station electrical generation, most notably, the MFGCR and the heterogeneous gas core reactor. Compact pulsed gas core reactor systems are also promising concepts for megawatt-range steady output or for applications requiring short pulses in the hundreds of megawatts. The nuclear space propulsion and power applications appear to be making a "comeback"; undoubtedly, the gaseous cores will be reanalyzed if an appropriate mission is identified.

Major obstacles to the establishment of a gaseous core reactor technology are materials compatibility, gas dissociation, fissile materials deposition, and gas handling and purification problems. Also, engineered safeguards will be required to detect and minimize gas leaks for closed systems.

Major advantages are dependent on the gaseous fuel state characteristics for the intended application. Obviously, the gaseous fuel "liberates" the core from cladding and fuel-imposed constraints and offers high fuel utilization for space missions. The gaseous core offers significant safety and operational advantages over solid fuels in the areas of stresses during launching, temperature, burnup-induced stresses and deformation, ease of disposal in space (including during potential reentry emergencies), and in refueling capabilities.

The leading gaseous core reactor concepts have reached an identifiable stage of scientific feasibility. Technical assessments indicate they are excellent candidates for space propulsion and special power applications. Terrestrial applications appear to be severely limited, given the present developmental climate; consideration for large commercial power stations is not foreseen in this century.

REFERENCES

1. G. I. BELL, "Calculation of the Critical Mass of UF_6 as a Gaseous Core, with Reflectors of D_2O, Be and C," LA-1874, Los Alamos National Laboratory (Feb. 1955).

2. G. SAFONOV, "Externally Moderated Reactors," *Proc. 2nd United Nations Int. Conf. Peaceful Uses of Atomic Energy*, Geneva, 1958, Vol. 12, p. 705, United Nations, New York (1958).

3. R. G. RAGSDALE and R. E. HYLAND, "Some Nuclear Calculations of ^{235}U-D_2O Gaseous-Core Cavity Reactors," NASA-TN-475, U.S. National Aeronautics and Space Administration, Lewis Research Center (Oct. 1961).

4. R. E. HYLAND, R. G. RAGSDALE, and E. J. GUNN, "Two-Dimensional Criticality Calculations of Gaseous-Core Cylindrical-Cavity Reactors," NASA-TN-D-1575, U.S. National Aeronautics and Space Administration, Lewis Research Center (Mar. 1963).

5. L. O. HERWIG and T. W. LATHAM, "Nuclear Characteristics of Large Reflector-Moderated Gaseous-Fueled Cavity Reactors Containing Hot Hydrogen," *AIAA J.*, **5**, *5*, 930 (May 1967).

6. T. F. PLUNKETT, "Nuclear Analysis of Gaseous-Core Nuclear Rockets," *Nucl. Appl.*, **3**, 178 (Mar. 1967).

7. T. L. LATHAM, "Nuclear Criticality Study of a Specific Vortex-Stabilized Gaseous Nuclear Rocket Engine," E-910375-1, United Aircraft Corporation Research Laboratories (Oct. 1966).

8. T. S. LATHAM, "Nuclear Criticality Study of a Specific Light Bulb and Open-Cycle Gaseous Nuclear Rocket System," F-910375-a, United Aircraft Corporation (Sep. 1967).

9. T. S. LATHAM, "Summary of the Performance Characteristics of the Nuclear Light Bulb Engine," AIPP Paper 71-642, presented at AIPP/SAE 8th Joint Propulsion Specialist Conf., November 1972.

10. T. S. LATHAM, H. E. BAUER, and R. J. RODGERS, "Studies of Nuclear Light Bulb Startup Conditions and Engine Dynamics," 11-910375-4, United Aircraft Corporation (Sep. 1969).

11. R. E. HYLAND, "Evaluation of Critical Mass for Open-Cycle Gas-Core Rocket Reactors," *Nucl. Technol.*, **12**, 152 (Oct. 1971).

12. I. K. KIKOIN et al., "Experimental Reactor with Gaseous Fissionable Substance (UF_6)," *Proc. 2nd Int. Conf. Peaceful Uses of Atomic Energy*, Moscow, Vol. II, p. 232, United Nations, New York (1959).

13. C. B. MILLS, "Reflector Moderated Reactors," *Nucl. Sci. Eng.*, **13**, 301 (Aug. 1962).

14. G. A. JARVIS and C. G. BEYERS, "Critical Mass Measurements for Various Fuel Configurations in the LASL D_2O Reflected Cavity Reactor," Paper No. 65-555, American Institute of Aeronautics and Astronautics (June 1965).

15. G. D. PINCOCK and J. F. KUNZE, "Cavity Reactor Critical Experiment," NASA-CR-72234, Vol. 1, General Electric Company Nuclear Materials and Propulsion Operation (Sep. 1967).

16. G. D. PINCOCK, J. F. KUNZE, R. E. WOOD, and R. E. HYLAND, "Cavity Reactor Engineering Mockup Critical Experiment," *Trans. Am. Nucl. Soc.*, **11**, 29 (1968); see also NASA-CR-72415, General Electric Company, Nuclear Materials and Propulsion Operation (June 1968).

17. J. F. KUNZE, G. D. PINCOCK, and R. E. HYLAND, "Cavity Reactor Critical Experiments," *Nucl. Appl.*, **6** (Feb. 1969).

18. J. F. KUNZE, J. H. LOFTHOUSE, and C. G. COOPER, "Benchmark Gas Core Critical Experiment," *Nucl. Sci. Eng.*, **47**, 59 (Jan. 1972).

19. G. A. JARVIS, D. M. BARTON, H. H. HELMICK, W. BERNARD, and R. H. WHITE, "Research on Plasma Core Reactors," LA-6666-MS, Los Alamos National Laboratory (Jan. 1977).

20. E. C. GRITTON and B. PINKEL, "The Feasibility of the Gaseous Core Nuclear Reactor Concept for Electric Power Generation," RM-5721-PR, The Rand Corporation (June 1969).

21. A. S. SHENOY, J. R. WILLIAMS, and J. D. CLEMENT, "Measurement of Heat-Transfer Parameters for the Gaseous Core Nuclear Rocket," *Trans. Am. Nucl. Soc.*, **12**, 3 (June 1969).

22. J. R. WILLIAMS and J. D. CLEMENT, "The Georgia Tech Particle Seeding Experiment," *Proc. 1969 Coaxial Flow Gas-Core Nuclear Rocket Conf.*, Cleveland, Ohio, August 1969, U.S. National Aeronautics and Space Administration, Lewis Research Center.

23. J. R. WILLIAMS and S. V. SHELTON, "Gas-Core Reactors for MHD Power Systems," *Proc. Symp. Research on Uranium Plasmas and Their Technological Applications*, Gainesville, Florida, January 1970, University of Florida.

24. J. D. CLEMENT and J. R. WILLIAMS, "Gas Core Reactor Technology," *Reactor Technol.*, **13**, *3*, 226 (Summer 1970).

25. J. M. KALLFELZ and J. R. WILLIAMS, "Exploratory Calculations for a Gaseous Core Breeder Reactor," *Proc. AIAA/ANS 2nd Symp. Uranium Plasmas: Research and Applications*, Atlanta, Georgia, November 1971, p. 70, American Institute of Aeronautics and Astronautics.

26. J. R. WILLIAMS, "Breeding Power in Space," *Mech. Eng.*, **95**, *7* (July 1973).

27. J. R. WILLIAMS, "Report on the Status of Plasma Core Reactor Technology," *Proc. IEEE Int. Conf. Plasma Science*, Gatlinburg, Tennessee, October 27-30, 1975, Paper No. 306, Institute of Electrical and Electronics Engineers (1975).

28. J. R. WILLIAMS and J. D. CLEMENT, "Analysis of UF_6 Breeder Reactor Power Plants," *Proc. 10th Intersociety Energy Conversion Engineering Conf.*, Newark, Delaware, August 17-22, 1975, CONF-750812, p. 308 (1975).

29. N. J. DIAZ and E. T. DUGAN, "Heterogeneous Gas Core Reactors," U.S. Patent No. 4,415,525 (1983).

30. N. J. DIAZ and E. T. DUGAN, "Gaseous Core Reactors for Electrical Power Generation," *Atomkernenergie/Kerntechnik*, **36**, *3*, 188 (1980).

31. N. J. DIAZ, E. T. DUGAN, C. C. OLIVER, and R. A. GAITER, "Heterogeneous Gas Core Reactor and Dual Fluid Closed Cycle Power Conversion System," Final Report to U.S. Department of Energy, Agreement No. EN-77-5-05-5546, University of Florida, Gainesville, Florida (Dec. 1977).

32. RUST and CLEMENT, "UF_6 Breeder Reactor Power Plants for Electrical Power Generation," *Proc. Princeton University Conf. Partially Ionized and Uranium Plasmas*, Princeton, New Jersey, June 10-12, 1976, CONF-760646, p. 249, Princeton University (1976).

33. L. L. LOWRY, "Gas Core Reactor Power Plants Designed for Low Proliferation Potential," LA-6900-MS, Los Alamos National Laboratory (Sep. 1977).

34. D. M. BARTON et al., "Plasma Core Reactor Experiments," *Proc. IEEE Int. Conf. Plasma Science*, Paper 30-13, Institute of Electrical and Electronics Engineers (1977).

35. C. D. KYLSTRA, J. L. COOPER, and B. E. MILLER, "UF_6 Plasma Engine," *Proc. 2nd Symp. Uranium Plasmas, Research and Applications*, New York, 1971, American Institute of Aeronautics and Astronautics (1971).

36. E. T. DUGAN, "The Nuclear Piston Engine and Pulsed Gaseous Core Reactor Power Systems," PhD Dissertation, University of Florida, Gainesville, Florida (Mar. 1976).

37. N. J. DIAZ, E. T. DUGAN, and C. C. OLIVER, "Neutronics and Energetics of Pulsed Gaseous Core Nuclear Systems," Final Report to the National Science Foundation under Grant No. Eng 75-01437, University of Florida, Gainesville, Florida (May 1978).

38. N. J. DIAZ, E. T. DUGAN, and C. C. OLIVER, "Gas-Generator, Pulsed Gas Core Reactors," Disclosure of Invention, University of Florida, Department of Nuclear Engineering Sciences, Gainesville, Florida (Apr. 1979).

39. N. J. DIAZ, E. T. DUGAN, C. C. OLIVER, E. E. CARROLL, Jr., and E. D. WHITNEY, "Basic Feasibility Studies of Pulsed Gaseous Core Nuclear Systems," Final Report, National Science Foundation, Grant No. Eng-77-28034, University of Florida, Gainesville, Florida (1982).

40. "A Gaseous Core Reactor System Characterization for NASAP," COO-5071-1 (SAA-109), Southern Science Applications, Inc., Dunedin, Florida (Sep. 1978).